Chapter 8
Dynamic Analysis Methods and Procedures

8-1. Attributes of Dynamic Analysis Methods

A dynamic analysis method is identified by four attributes: (1) material behavior, (2) design earthquake definition, (3) dimensional representation of project conditions, and (4) model configuration. The first two attributes have been discussed in preceding chapters. They are briefly summarized below, followed by a more detailed discussion of the latter two attributes.

a. Material behavior. This attribute defines material behavior as either (1) linear-elastic or (2) nonlinear. Associated with each of these two types of material behavior is a unique criterion for establishing acceptable response. Refer to paragraphs 2-2*d*, 2-2*e*, and 3-10.

b. Design earthquake definition. This attribute establishes which of two options will be used to specify the free field ground motion for the design earthquakes. The options are (1) design response spectra and (2) ground motion time-history records. Refer to Chapter 5 for details.

c. Dimensional representation of project conditions. This attribute defines whether project conditions will be represented in (1) two dimensions or (2) three dimensions. Project conditions refer to the geometry of the dam, the foundation, and the reservoir that have an affect on the seismic response. Examples of features governing which of these two options is appropriate include such things as layout of the dam axis, shape of the dam monoliths, foundation conditions, and orientation of potential fault slips if applicable.

(1) Two-dimensional (2-D) analysis. In the analysis of most gravity dams, it is assumed that the dam is composed of individual transverse vertical elements or cantilevers each of which carry loads to the foundation without transfer of load between adjacent elements. This assumption also applies to most RCC dams including dams with transverse joints that separate the dam into several monoliths, and dams with monolithic construction that contain no transverse joints. This assumption is usually valid, and stress analyses including the dynamic stress analysis phase can be based on 2-D representation of the dam cross-section. The design example provided in Appendix D presents a typical 2-D analysis. It demonstrates the most common procedure where a 2-D cross section of the structure is analyzed. However, most principles and procedures applying to the 2-D analysis also apply, or may be adapted to a 3-D analysis discussed below.

(2) Three-dimensional (3-D) analysis. Occasionally there are exceptions to the assumption justifying 2-D analysis. Dams in narrow canyons with a large enough ratio of height of the dam to distance between abutments may cause significant two-way distribution of stresses. Dams which are aligned on a curved axis may also allow significant transfer of stress into the abutments by arch action. Unusual shaped monoliths where there is substantial variation in the transverse cross section across the width of the monolith also may not be analyzed satisfactorily by 2-D methods. Another exception occurs when the trace of a potential fault slip is not parallel or nearly parallel to the dam axis. In this situation, a 2-D foundation fault displacement analysis will not adequately represent project conditions. All of these situations indicate the need for 3-D analysis if the response is to be determined to a reasonable degree of accuracy.

(a) Ground motion direction. The 3-D analysis introduces additional variables into the dynamic analysis. One important variable is determining the critical direction of the horizontal ground motion. This introduces a second horizontal component of ground motion into the dynamic analysis. The critical direction is defined by transforming the design earthquake ground motion into a pair of orthogonal components. Since no method exists to determine the critical direction directly, it usually becomes necessary to make some rough approximations.

(b) Simplified approach. This approach to determining the critical horizontal direction of ground motion is to select two orthogonal direction vectors (in the horizontal plane), and assume that the critical tensile stress at various locations on the dam will occur when the direction of ground motion is near one or the other vector. Since the accompanying orthogonal ground motion component is small, the stresses are assumed negligible and are neglected. Often the direction vectors are assumed to be the upstream-downstream direction, and the cross-stream direction. This approach requires performing separate, independent dynamic analyses for the two orthogonal ground motion directions.

(c) Conservative approach. Another more conservative approach accounts for both orthogonal components of ground motion. It is necessary to perform the two dynamic analyses described above, but the first analysis includes the full magnitude design earthquake ground motion component acting in an assumed direction with a fraction of the design earthquake ground motion acting orthogonally. The second analysis includes the fractional part of the ground motion acting in the assumed direction and the full magnitude ground motion acting orthogonally. The fractional part of the design earthquake ground motion is usually assumed to be 30 percent of the design earthquake ground motion. In a response spectrum analysis, stresses produced by the two horizontal components of ground motion are added directly to produce the resultant stress component for horizontal ground motion. This resultant stress component is then combined with the stress component produced by the vertical component of ground motion using SRSS.

(d) Complexity of analysis. A 3-D analysis requires considerably greater effort to create the 3-D model as compared to a 2-D model, and may require a main frame computer and a substantial amount of computer time to perform the analysis. It also produces a large amount of output to evaluate and interpret. However, the general purpose structural finite element programs are continuously being improved and are much more user oriented than they were in the past. They have refined graphics capabilities which help greatly in checking for errors in the computer model input, and in displaying the stress output. Also, specialized post-processors are being developed so that results can be evaluated much more efficiently. These advances greatly enhance the practicality of the 3-D analysis.

d. Model configuration. This attribute of the dynamic analysis method is dependent on the type of model used to represent the dam-foundation-reservoir system. The three types of models used for dynamic analysis of gravity dams are (1) the “standardized” model developed by Chopra and used in his Simplified Method of Analysis, (2) the finite element-substructure model, and (3) the composite finite element-equivalent mass system model.

(1) Standardized model. This type of model is used in Chopra’s Simplified Method. It is based on standardizing certain parameters that define the dam-foundation-reservoir system. It recognizes the fact that these parameters have little variation within the range of geometry common to gravity dams. For example, the normalized fundamental mode shapes for six sample dam cross sections were studied and found to be almost identical. A standardized mode shape was then developed for use in the calculation procedure.

(a) Factors considered. In the latest version, the standardized model considers dam-foundation rock interaction, dam-reservoir effects, and reservoir bottom absorption. All of these factors are based on standard curves and formulae.

(b) Model limitations. The standardized model is the simplest of the three types of models. A computer is not required to formulate the model or even to perform the dynamic analysis. However, standardizing the mode shape, frequency, and other parameters makes this an approximate method limited strictly to the typical nonoverflow monolith shape.

(2) Finite element-substructure model. In this type of model, different techniques are used to represent the dam, foundation, and reservoir; however, by using common node points at the interfaces, a computer model is formulated that can be analyzed by conventional matrix methods.

(a) Dam. The dam is modeled as an assembly of discrete finite elements. Either solid quadrilateral plane stress or plane strain elements are used for a 2-D model.

(b) Foundation. The foundation is idealized as a viscoelastic half-plane. The elastic properties of the foundation are formulated into a substructure matrix using the theory of elasticity. This matrix is combined with the structural stiffness matrix developed from the finite element representation of the dam. The substructure matrix introduces the foundation stiffness to the equations associated with the degrees-of-freedom of the node points at the dam-foundation interface. There is no finite element model of the foundation. The dimensions of the structural stiffness matrix are set by the finite element model of the dam.

(c) Reservoir. The impounded water of the reservoir is idealized as a fluid domain of constant depth and infinite length. This can be interpreted as a series of subchannels of infinite length discretized to match the common upstream nodal points of the dam. The reservoir bottom absorption is modeled by adjusting the boundary condition at the reservoir bottom. This substructure representation of the reservoir produces more accurate hydrodynamic response to horizontal and vertical ground motion than does an equivalent mass system representation as described in paragraph 8-1*d*(3)(a).

(d) Specialized computer program. This type of model requires a specialized computer program to allow the foundation and the reservoir effects to be formulated in the manner described above. Also, the substructure method requires the foundation to be modeled as a uniform homogeneous material. Presently, a computer program is available which develops a 2-D finite element-substructure model for gravity dams. Refer to paragraph 8-2*b*.

(3) Composite finite element-equivalent mass system model. This method models both the dam and the foundation as an assembly of discrete finite elements. Either solid quadrilateral plane stress or plane strain elements are used for 2-D models or 3-D isoparametric solid elements are used for 3-D models. The foundation consists of a rectangular block with a width in the upstream-downstream direction about 3 times the base width of the dam at the foundation plane, and with a height about 1.5 times the height of the dam.

(a) Reservoir effects. The reservoir effects are modeled by developing an equivalent mass system which consists of adding mass to the finite element model to correctly alter the dynamic properties. The added mass is active in the direction normal to the vertical upstream face of the dam. This method also allows the reservoir bottom absorption characteristics to be incorporated into the analysis by using Chopra's standard hydrodynamic pressure function curves to determine the added mass. Although use of these curves in developing the equivalent mass system is only approximate, it has been shown to be reasonably accurate. Refer to paragraphs 7-5*c* and 7-5*d* and Appendix D for details.

(b) Boundary conditions. With this type of model, the earthquake ground motion is introduced at the rigid boundary. This boundary is along the sides and bottom of the rectangular foundation block rather than at the ground surface (dam-foundation interface) where the design earthquake ground motion is specified. To account for this, the foundation is assumed massless. Therefore, no wave propagation takes place in the massless foundation so the ground motion is transmitted to the dam-foundation interface without modification.

(c) Flexibility in modeling. The composite finite element model may be formulated to represent a variety of design conditions for both 2-D and 3-D models. For example, most any geometric shape may be accommodated, various zones of superior RCC mix may be incorporated in the dam model, and discontinuities such as fault zones or changes of deformation modulus in the foundation may also be included.

8-2. Comparison of Dynamic Analysis Methods

This section will describe the attributes associated with the most commonly used dynamic analysis methods, and the methods will be evaluated and compared.

a. Chopra's simplified method. This method uses the standardized model described in paragraph 8-1*d*(1). Other attributes include 2-D representation, linear-elastic material behavior, and response spectrum definition of the design earthquake. This method is not flexible because all of these attributes are fixed.

(1) Equivalent lateral force. The simplified method develops the maximum response to the first mode as a set of equivalent lateral forces. It also approximates the equivalent lateral forces associated with the higher vibration modes using a "static correction" method. The two sets of equivalent lateral forces are treated as statically applied distributed lateral loads. At present, response to a vertical component of ground motion is not possible with this type of model. Stresses may be hand calculated by beam theory treating the dam as a simple cantilever beam, or the static load may be applied to a finite element model of the dam to gain a more realistic stress distribution pattern.

(2) Advantages and limitations. The simplified method is easy to use and can be done without a

computer. However, it takes less time and effort to perform a simple 2-D analysis using a general purpose finite element program on a personal computer (PC) and the results of the finite element analysis will be more accurate. Also, comparative studies have indicated that as the flexibility of the foundation increases, the response calculated by the simplified method tends to diverge from the response determined by more refined methods, and the simplified method is not always conservative.

(3) Recommended use. Because of the limitations of the simplified method, it should be used only for preliminary design work as described in paragraph 8-4*a*. However, appropriate equations and design figures used in this method are helpful in checking the results from other more refined analyses and to prepare the computer input for these methods.

b. EAGD-84 Analysis Method. EAGD-84, A Computer Program for Earthquake Analysis of Concrete Gravity Dams (Fenves and Chopra 1984), is a specialized computer program that allows the foundation and the reservoir effects to be characterized by the substructure model described in paragraph 8-1*d*(2).

(1) Other attributes. Other attributes that define the EAGD-84 analysis method include 2-D representation, linear-elastic material behavior, and time-history ground motion definition of the design earthquake. All attributes of EAGD-84 are fixed and cannot be changed.

(2) Advantages and limitations. When compared to either a standardized model or a finite element-equivalent mass system model, the EAGD-84 substructure model is a better representation of the foundation and reservoir, as long as the project conditions properly fit the program requirements. Also, the time-history definition of ground motion is a level of refinement beyond response spectrum definition. Therefore, the EAGD-84 method is capable of producing the most accurate response, and the time-history response output provides additional information often needed to evaluate acceptable performance. The biggest disadvantage of EAGD-84 is the lack of attribute flexibility.

c. General purpose finite element program analysis methods. This comprises a number of methods each with a different combination of attributes, but all having the composite finite element-equivalent mass system model as a common attribute. These methods use any one of several proven general purpose finite element computer programs to perform the dynamic analysis. Examples are ANSYS, SAP6, GT-STRUDL, and STAAD III. The material behavior attribute for most of the general purpose programs is linear-elastic; however, some programs such as ANSYS and ADINA have nonlinear capability.

(1) Primary advantage. Attribute flexibility is the primary advantage of the general purpose finite element methods. Except for the common attribute mentioned above, design methods are possible which feature most of the other possible combinations of the remaining attributes. This allows the dynamic analysis phase to start with a simple method such as the 2-D, linear-elastic, response spectrum method. If the results of the simple analysis or the project conditions indicate the need of a more refined analysis, the procedure may transition conveniently into a more refined analysis by modifying or adding to the input to the same general purpose program.

(2) Other advantages. The general purpose finite element programs discussed above are large, comprehensive programs developed for main frame computers. In addition to these programs are several smaller general purpose finite element programs specifically developed for PC's. Since these desk-top PC's are now a standard item in most design offices, a considerable amount of the dynamic analysis phase may be completed without the need or expense of a large main frame computer.

8-3. Dynamic Analysis Procedure

The dynamic analysis procedure described hereafter is derived with the objective of arriving at a reasonable and economic design of a new dam, and evaluating the seismic resistance of existing dams using an analysis method with the simplest attributes possible. In general the procedure is to perform a dynamic stress analysis and evaluate the results to determine if the RCC dam response to the design earthquakes is acceptable. If not acceptable, the design of a new dam may be modified and reanalyzed, or a more refined analysis method may be employed when analyzing either new dams or existing dams.

a. Evaluating acceptable response. The response is judged acceptable for a linear-elastic analysis when the tensile stresses are within the established allowables and the analysis method provides a reasonably accurate or conservative representation of project conditions. Should the analysis method utilize an extremely simplified representation of project conditions, the response may not necessarily be conservative and will likely be of relatively low order of accuracy. However, the response may still be judged acceptable without pursuing more refined analyses on the basis that the tensile stresses are far enough below the established allowables to clearly infer that the response satisfies the requirements and criteria described above. Refer to paragraphs 2-2*e*, 2-2*f*, and 2-2*g* for information on allowable tensile stress criteria for various methods of analysis.

b. Modifying the design of a new dam. When the response from a dynamic stress analysis for a new dam is judged not acceptable, consideration shall be given to modifying the design, adjusting the computer model to reflect the modifications, and reanalyzing. Modifications include:

(1) Modify geometric configuration.

(2) Superior mixes. Use richer, higher strength superior RCC mixes in overstressed areas.

(3) Reducing aggregate size. Increase tensile strength by reducing the maximum size aggregate.

(4) Mortar bedding. Provide mortar bedding to increase tensile strength at lift joints.

(5) Zone boundaries. Adjust the zone boundaries of the superior RCC mixes to better fit the tensile stress pattern.

c. Refining the dynamic analysis methods. When the response from a dynamic stress analysis of an existing dam is judged not acceptable, the next step in the procedure shall be to reanalyze using an analysis method with more refined attributes. In contrast to this, there is no clearly defined point in the design procedure for new dams that indicates when the analysis method should be refined. The design conditions and results of the design procedure already completed must be evaluated to determine when it is appropriate to suspend the design modification process, and pursue a more refined analysis of the latest modified design. When the attributes of the dynamic analysis method are to be refined, it is recommended that the refinements be considered in the following order:

(1) 3-D representation. Consider refining the analysis from two to three dimensions when the accuracy of the response from a 2-D analysis cannot lead to a confident judgment that the response is acceptable.

(2) Time-history analysis. Consider defining the design earthquakes with appropriate ground motion time-history records, and performing a time-history analysis when additional insight into the structural behavior beyond that provided by the response spectrum analysis is needed. A time-history analysis yields additional information regarding the excursions of tensile stress cycles beyond the allowables and provides a better understanding of the response. This applies both to existing dams or to the design of a new dam when all practical and economical modifications to the design of a new dam have been exhausted.

(3) Nonlinear analysis. The analysis based on nonlinear material behavior represents the greatest possible refinement and it produces the most accurate results. However, it is also the most complex and the most costly. It requires time-history ground motion input, direct integration solution, a large main frame computer, specialized computer programs, and a considerable amount of computer time. As such, it is the last recourse in the attribute refining process. The nonlinear analysis should only be undertaken under the guidance of an expert in the field of fracture mechanics and finite element methods.

8-4. Preliminary Design of New Dams

Preliminary design includes engineering and design through the Feasibility Phase, or through the General Design Memorandum (GDM) phase if a GDM is prepared for the project.

a. Initial dynamic analysis. The initial dynamic stress analysis shall use the simplest analysis method which is identified by the following attributes: (1) linear-elastic material behavior, (2) 2-D representation, and (3) design response spectrum definition of the design earthquake. The analysis shall be performed using the cross-section of the critical transverse element of the dam which usually consists of a section of the nonoverflow monolith with the greatest height. The dam-foundation-reservoir system shall be represented by a composite finite element-equivalent mass system model for RCC dams subject to critical seismic design conditions. For other conditions, the dam-foundation-reservoir system may be characterized by either the standardized model using Chopra's simplified method or the composite finite element model described above.

b. Seismic and foundation investigations. Appropriate investigations of the regional tectonics and site seismicity shall be conducted at the preliminary design stage. When required, the site-specific design response spectra shall be developed in accordance with paragraph 5-5*c*. Preliminary dam site and reservoir geology investigations shall be conducted including exploratory corings and load testing to determine foundation conditions and deformation modulii.

c. Tensile strength. For preliminary design, the tensile strength may be taken from Figures 3-1 through 3-6 for the proposed basic RCC mix and for superior RCC mixes in the critical zones.

d. Satisfying criteria. The preliminary design procedure shall progress to the point where it becomes evident that the preliminary design will lead to a final design that fully satisfies established performance requirements and criteria.

8-5. Final Design of New Dams

The final design of an RCC dam shall result in a design that satisfies the provisions of this EP. The dynamic analysis phase for RCC dams under critical seismic design conditions shall be presented in an appropriate feature design memorandum.

a. Final design analysis method. The dynamic analysis method for the final design shall evolve from the simple initial method described in paragraph 8-4*a* to more refined methods of design conditions as warranted. RCC dams analyzed by Chopra's simplified method during the preliminary design phase shall be reanalyzed using a composite finite element-equivalent mass system model and general purpose finite element program in the final design.

b. Foundation and material investigations. The foundation conditions for the final design shall reflect the latest exploratory coring and other foundation and geology investigations. The final design shall be based on the RCC material properties obtained from tests on core samples taken from test fill placements made with the proposed design mixes.

8-6. Evaluating Existing Dams

The dynamic analysis procedure for evaluating existing dams is essentially the same as the combined preliminary design and final design procedures for a new dam, except modification of the design discussed in paragraph 8-3*b* does not apply to existing dams. As with the design of new dams, the dynamic analysis procedure shall utilize an analysis method with the simplest attributes possible to determine if the existing dam is capable of responding to the design earthquakes in an acceptable manner.

a. Material properties. Material properties of the RCC for an existing dam, including tensile strength, shall be obtained from tests on core samples taken directly from the dam.

b. Using available records. Exploratory coring logs, laboratory test data, and field geologic test results conducted during design and construction should be used for an existing dam and to provide information needed to model the foundation. Reservoir data should be used to determine the reservoir and tailwater elevations for earthquake load cases.

c. Special requirements and analysis methods. The regional tectonics and site geology and seismicity shall be investigated as required to develop a site-specific design response spectra in accordance with paragraph 5-5*c*. The initial analysis of an existing dam shall utilize a composite finite element-equivalent mass system model. Existing dams shall not be analyzed by Chopra's simplified method.